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Subseabed Disposal of Nuclear Wastes

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The management of radioactive wastes has received new emphasis in recent years because of increasing concerns with environmental effects over very long periods of time and because of the expansion of nuclear technology in the United States and abroad (*1*).

Summary. Fine-grained clay formations within stable (predictable) deep-sea regions away from lithospheric plate boundaries and productive surface waters have properties that might serve to permanently isolate radioactive waste. The most important characteristics of such clays are their vertical and lateral uniformity, low permeability, very high cation retention capacity, and potential for self-healing when disturbed. The most attractive abyssal clay formation (oxidized red clay) covers nearly 30 percent of the sea floor and hence 20 percent of the earth's surface.

Much effort has been expended in researching geologic media on the continents, yet two-thirds of the planet's geology (submarine) has been largely ignored. Although there are not sufficient data now to assess the technical feasibility of subseabed disposal of nuclear wastes, enough is known to define the questions as well as the systematic interdisciplinary efforts required to answer them. We believe that we have identified a geologic formation that deserves careful study as a possible repository medium; in this article we will outline our reasons for this belief in the context of present waste management strategies (*2*).

Our primary objective in this article is to stimulate discussion within the many scientific disciplines that should be involved in assessing the feasibility of disposing of processed and packaged high-level nuclear waste (*3*) in geologic formations beneath the world's oceans (*4*) (Fig. 1). High-level waste is considered the most difficult radioactive waste to dispose of because of its heat, radiation output, and longevity (*5*). If subseabed disposal is found to be feasible for such wastes, then other factors such as cost will become dominant in determining whether it should also be used for other nuclear and perhaps even hazardous chemical wastes. The United States should also assess the marine nuclear waste disposal programs of other nations.

Two basic questions must be answered in order to evaluate the environmental, technical, and engineering feasibility of the subseabed disposal concept:

1) Is there a barrier or set of barriers (*6*), natural or man-made, that will offer satisfactory containment of radionuclides? The natural barriers that have been considered are basement rock, sediments, and ocean water, and the man-made barriers are the waste form, canister, and "sacrificial" layers (overpacks). Of the natural barriers, basement rock (basalt) has not been considered further because of its extreme lateral variability (*7*) and locally high bulk permeability (*8*). Ocean water has also not been pursued because deep ocean water has too short a mixing time (on the order of 10^3 years) to act as a barrier to the movement of long-lived nuclides, even though it does effectively bar man from potential disposal sites.

2) Will these barriers still be adequate after the introduction of waste containers? Key issues raised by this question include the effectiveness of hole closure after physical disruption of sediments, and the effects (possibly synergistic) of heat and radiation on the barrier properties of waste form, canister, and sedimentary materials.

It is clearly impossible to perform experiments for the expected life of a repository—10^5 to 10^6 years. Therefore we must rely on models of repository, canister, and waste form behavior to predict the future capabilities of a disposal scheme to contain nuclear waste. The process of evaluating a waste disposal scheme consists largely of the construction and verification of such models.

Site Selection

Limited resources are available for evaluating the concept of subseabed disposal. In order to use these resources productively, effective strategies must be divised for selecting acceptable geologic formations and for assessing the scientific and engineering feasibility of the concept.

Strategy for site studies. Since the geologic formations beneath the oceans are vast (covering about 70 percent of the surface of the globe) and the resources available to study them are small, we have developed a methodology which, after the appropriate research has been completed, will allow acceptable sites to be identified. The approach (*9*) involves the following steps:

1) Development of a list of exclusionary criteria to decrease the global area under consideration to a manageable size.

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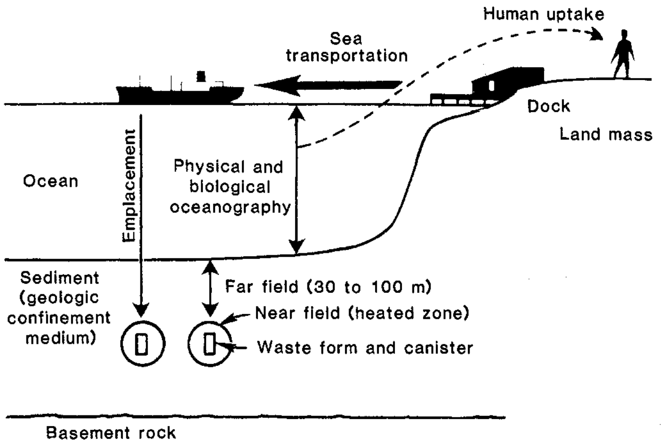

Fig. 1. Schematic showing range of considerations in examining the feasibility of subseabed waste disposal. It is necessary to characterize the geological barrier and consider the results of leakage or accidental failure to emplace the canister within deep-sea sediments. One must be able to trace the migration of escaped radionuclides from the canister site within and through the sediments, water column, and ecosystem in order to evaluate the potential environmental impact of subseabed nuclear waste disposal (not to scale).

2) Ranking of the areas not excluded in step 1 by use of historical (archival) data.

3) Acquisition of additional reconnaissance information for smaller areas of interest.

4) Selection of potential sites and acquisition of site-specific data by which they can be ranked.

5) Concentration on one or more sites in each of the two oceans (Atlantic and Pacific) from those still considered acceptable for long-term engineering and environmental studies.

Site evaluation. In this study, we have focused on deep-sea formations that are geologically stable and uniform and that have spatially and temporally predictable properties. The identification of regions beneath the sea floor that are stable, uniform, and predictable depends on several principles of modern marine geology.

The submarine physiographic elements of our planet result from lithospheric plate motions. Plate collision or subduction typically yields deep-sea trenches, whereas plate separation or spreading yields mid-oceanic ridges that subside into abyssal hill terrains as they cool. Plate slippage or translation along faults such as the San Andreas yields rugged fracture-zone topography. Variations in the rate of accumulation of sediment modify this basic crustal morphology.

Wind stress and the density changes that result from evaporation and precipitation produce surface and subsurface currents in the ocean. Where surface currents diverge, relatively cold but nutrient-rich deeper water wells up to the sunlit (photic) zone and supports high biological productivity. The same process occurs where strong offshore or longshore winds push surface waters seaward from continental margins, or where nutrients are introduced from the land. In such biologically productive regions (*10*), vast amounts of skeletal debris fall to the seabed, where, in the absence of dissolution and dilution by inorganic debris, they form geologic formations called carbonate or siliceous oozes (depending on composition). These formations, which cover approximately 50 percent or about 200×10^6 square kilometers of the ocean floor, are commonly found at depths of 2 to more than 5 km.

Ocean margins beyond the continental shelf are characterized by sediments called hemipelagic mud, which contain biogenic remains mixed with weathered rock particles and other debris from the continents. This material, which is rich in organic carbon (as much as a few percent) compared with other deep-sea sediments, covers about 20 percent or 50×10^6 km^2 of the ocean floor.

Away from the biologically productive areas are vast open ocean regions, where a slow rain of windblown particles from land, meteoric and volcanic dust, insoluble biogenic debris, fine precipitates from mid-ocean ridge hydrothermal systems, and authigenic minerals accumulates on the sea floor. In the absence of redistribution by bottom currents or turbidity currents, these materials produce a unique geologic formation that blankets about 30 percent (100×10^6 km^2) of the sea floor. This dark, chocolate brown, fine-grained (average particle size much less than 5 micrometers), extremely cohesive sediment is called abyssal red clay. It is generally found away from plate boundaries in deep (greater than 5 or 6 km) open ocean areas seaward of the continental margins and abyssal plains. Its rate of accumulation is on the order of 0.1 to 10 millimeters per 1000 years. This rate, coupled with a continually renewed supply of oxygen in abyssal waters (generally 3 to 6 milliliters per liter), produces an oxidized deposit low in organic carbon (commonly less than 0.1 percent by weight). In many of the ocean basins, plate motions have carried sites from one depositional regime to another, resulting in the superposition of different sediment types.

We believe that certain of these deep-sea formations may be able to contain nuclear wastes in that they combine desirable barrier properties (see below) with continuous, stable (*11*) depositional histories. We argue that predictions of future geologic stability can only be credible for regions where the desired stability has prevailed and can be demonstrated over a period of time at least an order of magnitude longer than that required for waste isolation. Therefore, if an isolation period of the order of 10^5 to 10^6 years is required, a continuous geologic record of past environmental

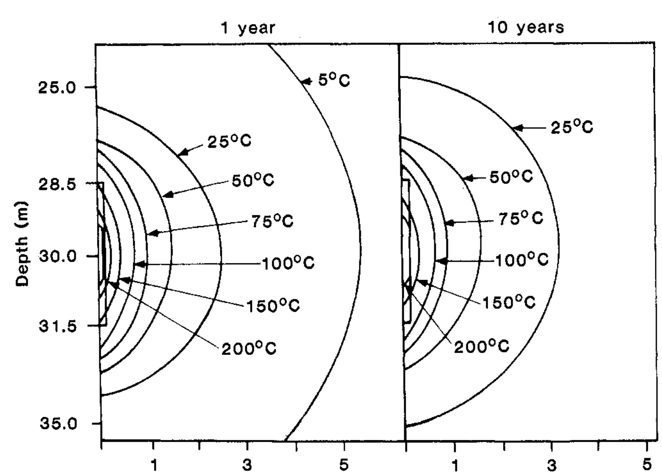

Fig. 2. Predicted isotherms around a canister containing 1.5 kilowatts of high-level waste at 1 and 10 years after burial. Note that the maximum extent of the 100°C isotherm, the temperature below which it now appears that significant hydrothermal alteration of the sediment will not occur, is less than 0.8 m from the canister. The region within this isotherm (near field) is small in volume (about 5.5 m^3) relative to the volume in the tens of meters of sediment above the canister. Thus, although the chemical environment within the 100°C isotherm may be significantly altered, the effects on the total geologic barrier are minor.

stability for at least 10^7 years should be demonstrable. Because large regions of the deep ocean basin are, and have been, sites of continuous deposition, the selection of relatively small [10^4 km^2 (*12*)] areas with continuous geologic records spanning tens of millions of years is relatively easy (*13*).

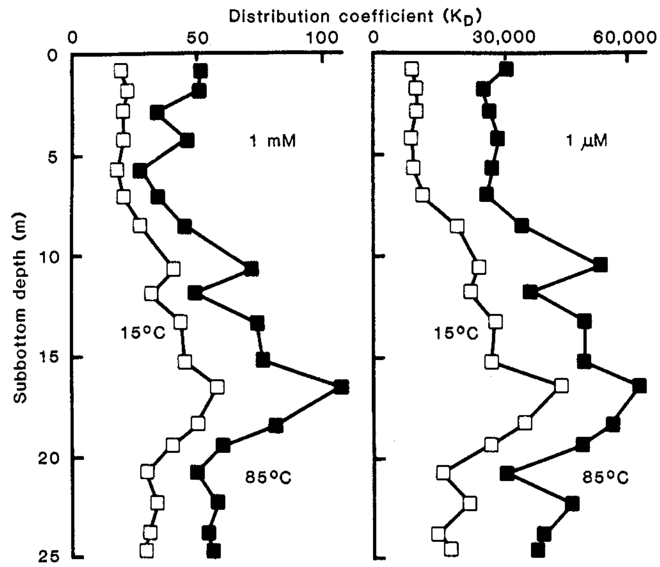

Fig. 3. Distribution coefficients for 1 millimolar and 1 micromolar Eu in 0.68 *N* NaCl for a profile of North Pacific sediments (core LL44-GPC3, 33°19.9′N, 157°49.4′W); □, 15°C experiments; ■, 85°C experiments. These data show the variability in K_d values to be expected in mid-ocean deep-sea clays; the temperature dependence of K_d (a 70°C temperature rise roughly doubles K_d for most sediments); and the very marked concentration dependence of K_d (given roughly by K_d [Eu]$^{-0.9}$).

Because water-saturated sediment is an excellent medium for the propagation of sound, the lateral and vertical continuity and uniformity of these deposits can be tested by standard acoustic (seismic) reflection techniques from either surface ships or, for very high resolution, towed near-bottom vehicles. The acoustic records can be calibrated with sediment cores, which are recovered routinely by piston coring or from the deep-sea drilling ship *Glomar Challenger*.

In summary, the chances of finding a potential waste repository are greatest away from plate boundaries, where geological perturbations such as large earthquakes, volcanoes, or faults disrupt the uniform layers of sediment, and away from areas of steep or rugged topography, where slumping or erosion by deep-sea currents may interrupt the continuous deposition of fine sediment. In order to minimize interference from human activities, areas that contain natural resources such as major fisheries or exploitable hydrocarbon or mineral deposits should also be avoided (*14*).

The Multiple-Barrier Principle

One way of assessing a proposed repository is to balance the rates of decay of the radionuclides against the rates at which they migrate toward man. In a subseabed disposal system, the waste form, the canister, and the sediments within the maximum extent of the 100°C isotherm (called the near-field environment; see Fig. 1) would be the primary barriers during the thermal period of about 500 years. The thermally unaltered sediment outside the 100°C isotherm (far-field environment) would be the primary barrier for long-term containment. The benthic boundary layer and the water column, although already part of the biosphere, are significant diluent and access barriers (*6*).

Since waste-isolation times of the order of 10^5 to 10^6 years prohibit real-time experiments to demonstrate containment, we must use mathematical models to predict the response of each barrier and assess its adequacy.

Near-field interactions. Nuclide movement through the sediment is driven by chemical and physical gradients, which are determined by the natural or modified properties of the sediment. During the first few years after waste emplacement, the fission product–dominated output of heat, radiation, and ions would induce chemical, physical, and mechanical gradients different from those naturally present. Accurate determination of these gradients will be critical in predicting the integrity of waste form, canister, and nearby sediments.

In red clay sediments, which have very low permeabilities [10^{-6} to 10^{-7} centimeters per second for a unit hydraulic gradient (*15*)], heat is transferred from the canister by conduction; the maximum convective displacement of a water particle originating on top of a canister in such sediment, given the thermal system defined below, is only about 30 cm (*16*). The thermal conductivity of the sediment is nearly constant at 1 watt-meter per degree Celsius over the temperature range 25° to 300°C. Considerations of chemistry require that the temperature at a canister wall not be allowed to exceed about 250°C. This restriction, combined with a thermal conduction model (*16*), the measured thermal properties of red clay sediment, a canister geometry of 0.3 by 3 meters, and an exponential thermal decay curve for 10-year-old waste, yields an upper limit of 1.5 kilowatts for the initial thermal output of each canister. The maximum dimensions of the 100°C isotherm surrounding the canister would be limited in both space and time; the radius of the isotherm would be less than 1 meter at its maximum extent (Fig. 2). In these calculations it is assumed that there is no significant thermal or chemical interaction between canisters, a restriction of no practical concern since canisters need not be emplaced less than 100 m apart.

At pressures corresponding to subseabed disposal depths (500 to 600 bars at 5000 to 6000 m) seawater does not boil (*17*). The density of seawater does decrease by approximately 15 percent for a temperature increase from 2° to 250°C, however (*18*). A major emphasis of our study at present is on determining whether such a density and corresponding strength change in the sediment could lead to sinking of a waste canister or flotation of a bolus of warmed sediment. Preliminary model calculations suggest that both phenomena would occur but that the displacements would be very small. Because of the dearth of theory and data on appropriate material properties, we expect the unequivocal resolution of this problem area to take several more years.

When samples of seawater and water-sediment mixtures are heated to 300°C at high pressures, the solution *p*H changes from 8 to 3. Below 250°C the *p*H change is less marked (*16*). For a canister with a peak wall temperature of 250°C in illitic red clay sediment, calculations suggest that less than 2 cubic meters of unheated sediment would be needed to neutralize all the acid generated in the thermally perturbed region of about 5.5 m^3 (*19*).

A large number of canister materials have been evaluated for corrosion rates in oxygenated and deoxygenated seawater environments. At this time the most promising candidate for a canister endurance of 500 years is Ticode 12 (*20*). The corrosion behavior of this material in seabed environments at elevated temperatures, pressures, and radiation levels is under investigation.

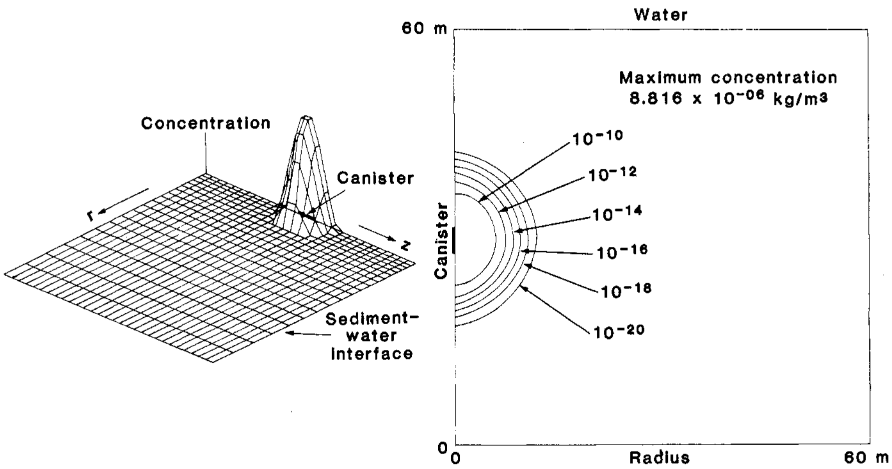

Fig. 4. Long-lived isotopes with high K_d's, such as ^{239}Pu, will decay in place with virtually none reaching the surface. The predicted axisymmetric distribution of ^{239}Pu about a buried canister after 100,000 years is shown. Although 4.1 half-lives of ^{239}Pu have elapsed, a little less than one-third of the original inventory remains because of the decay of ^{243}Am to ^{239}Np and then to ^{239}Pu.

Far-field interactions. The plastic sediments beyond the near-field form the primary long-term geologic barrier to the migration of radionuclides. Movement through these sediments is by diffusion, convection, advection, or combinations thereof, and can be driven by either natural or artificially induced gradients.

The only known natural driving forces for pore-water movement within flat-lying deep-sea sediments are compaction and geothermal heating. Existing permeability data for both undisturbed and remolded sediment suggest that, in the absence of geothermal circulation, the natural pore-water velocity is comparable to the rate of sediment accumulation (0.1 to 10 mm per 1000 years). Thus, in the absence of an anomalous geothermal flux (*21*), pore water from deep within the sediments will not reach the sediment-water interface (*22*).

One of the most important far-field geologic processes is sorption of waste elements onto solid particles, the magnitude of which can be specified by a distribution coefficient (K_d). This is the ratio of the concentration of a sorbed chemical species (in this case of a radionuclide) to the concentration of the same species in solution in the pore waters of a given volume of saturated sediment (*23*). A large K_d indicates strong sorption; the larger the value, the larger the proportion of the chemical species attached to solid particles relative to that dissolved in the surrounding pore water. For a given element, K_d varies with temperature, concentration of the species of interest, solution composition, and the nature of the solid substrate (*24*). Existing data show that for trace concentrations, the K_d's for cations such as calcium, strontium, barium, thorium, and europium vary by less than a factor of 10 among the three major sediment types: hemipelagic muds, pelagic red clays, and biogenic oozes. Most such values for dilute cation solutions are in the range 10^3 to 10^6 milliliters per gram (*24*). Laboratory batch sorption coefficients for red clay sediment have been measured for many radionuclides at 15° and 85°C (Fig. 3). North Pacific clay sediments have some of the highest K_d values for cations of any geologic medium examined to date. For anionic species such as I^- or TcO_4^-, oxidized pelagic sediments have K_d's very close to zero. Values for $Tc\ O_4^-$ in reduced (S^{2-}-bearing) sediments, however, can exceed 10^2 ml/g (*25*).

Results from our thermal model and sediment-nuclide interactions have been combined in a computer model to calculate ion concentrations around a buried source as a function of time (Fig. 4) (*16*). Initial estimates suggest that for a 1.5-kilowatt decaying heat source (i) a water molecule will be transported by thermally induced movement approximately 0.3 m in 1000 years (after which, effectively, all the heat is gone), and (ii) a radionuclide with a distribution coefficient of 10^3 to 10^6 ml/g, a half-life of less than 500,000 years, and a burial depth of 15 m or more in the sediment will not reach the benthic boundary layer at the surface of the sediment before it has decayed essentially to zero concentration.

The water column. Recent advances in physical oceanography have shown that the circulation of the oceans is far from uniform (*26*). Mean flows are rarely as energetic as fluctuations, and the temporal and spatial variability of such fluctuations is still essentially unpredictable. It is clear, however, that the seas are well mixed on time scales of thousands of years. Calculating mixing (or stirring) rates and directions for times shorter than these will require considerable study. Thus, the ocean is not a good primary barrier. However, it can dilute and disperse harmful materials, as well as provide an imposing barrier to human access to a repository, even at current levels of technology.

Other Considerations

Emplacement. Only conceptual outlines of potential emplacement methods have been developed thus far. The free-fall penetrometer is the simplest concept, but it relies on terminal speeds being adequate to penetrate the sediment to sufficient depths and on holes closing behind without mechanical aids. If sufficient depths cannot be achieved with a free-fall penetrometer, a boosted version is the next least complex emplacement system. The boosting system might be a launch tube held just above the sediment surface, from which the penetrometer could be fired downward by use of a propellant. Present navigational techniques would allow guidance of a penetrometer to within a few meters of a desired spot [a requirement for any subsequent recovery by an overcoring device (*27*)]. This method employs techniques that are currently available or close to state-of-the-art technology.

If hole closure cannot be ensured for the penetrometer emplacement method, an injector system might also be employed with either a cable-lowered device or coring technology comparable to that now in use by the Deep Sea Drilling Project (*28*). In the latter case, the emplacement operation could be controlled inside the drill string, which is able to penetrate several hundred meters below the sea floor. Withdrawal of the injector system would create suction forces that would tend to close the hole.

In all cases, the emplacement hole must close or be closed (backfilled) immediately after emplacement of the waste. Initial laboratory work on dynamic penetration of a canister into viscoelastic red clays suggests that the hole may close rapidly after fast penetration (*29*). Detailed predictive models for both rapid and slow insertion are being developed, and in situ field validation tests will be completed before acceptance of any emplacement concepts.

Transportation and storage. We assume that solidified high-level waste would be transported by land to a coastal embarkation point. Such transportation would be done by conventional methods now under development by the transportation division of the Department of Energy (*30*). For the reference penetrometer emplacement system, the waste, packaged in a specially designed penetrometer container or overpack, would be placed aboard a combination transport-emplacement ship and carried to the disposal area. Each penetrometer would be fitted with locating devices and recovery mechanisms. The locating devices (transponders) would be designed for an operational life of several years. Such devices would be used to locate any waste container lost before emplacement. After emplacement, the location of each canister in the sediment would be precisely determined by use of a deeply towed "fish" (*31*) fitted with sub-bottom acoustic-magnetic sensor systems.

Institutional. Article IV(1)(a) of the London Dumping Convention prohibits the "dumping" of high-level waste or spent fuel *into* waters of the oceans (*32*). Our concept involves neither dumping, as defined by the convention, nor placement of wastes in the waters of the ocean or *on* the seabed. Instead, we are assessing the feasibility of precisely engineered placement within a suitable geologic formation *beneath* the seabed. If this concept is practical, it will be critical to establish a national and international framework within which the option can be used. Currently, an international study group of eight nations exchanges technical details on the subseabed disposal option (*33*).

Relative costs. It is inappropriate, if not impossible at this time, to estimate detailed costs of a subseabed emplacement system. However, crude comparisons with continental geologic disposal options provide a sense of relative costs and a starting point for more sophisticated cost analyses. We suggest that the costs of packaging and land transportation of waste to a land disposal site or a port facility would be comparable. The receiving and ship-loading facility for our concept can be compared to the aboveground facilities at a mined geologic repository. The transport and emplacement ship would cost approximately one-sixth the amount required to dig the shafts and drifts for a repository in granite. Costs of emplacement within the sediments would be similar to costs for the operational phase of a mined repository. For a mined repository there is an additional cost for backfilling and shaft sealing. The shutdown cost of the subseabed repository is estimated to be zero; the decommissioning and decontamination (D & D) costs of the dock and ship facilities should be comparable to the D & D costs of the aboveground facility at a mined repository. Thus, our preliminary estimate is that the costs of the two options are of the same order.

Conclusion

Shortly before his death, the well-known oceanographer John D. Isaacs wrote: "Perhaps the most important relationship of the ocean to human power needs in the future will be in the employment . . . of the deep region below the sea floor for the disposal of nuclear waste" (*34*). We are committed to a rigorous and open assessment of this possibility (*35*).

References and Notes

1. U.S. Department of Energy, *Spent Fuel Storage Fact Book* (DOE/NE-0005 UC-85, Washington, D.C., April 1980). A 1000-megawatt light water nuclear reactor produces 350 cubic feet of spent reactor fuel or 35 cubic feet of solidified high-level waste per year. We estimate that by the year 2000, the volume of solidified waste from power reactors will be 8×10^4 cubic feet of high-level waste (less than 1 percent of the volume of a single supertanker) or about 5×10^4 canisters (0.3 by 3 meters) with 20 percent waste loading. Assuming 400 cans per emplacement ship, it will require 50 shiploads to dispose of all the waste generated to 1995.
2. Among the major components of the Department of Energy's strategy are (i) mined repositories in appropriate geologic formations should form the first disposal sites in the United States; (ii) deep-ocean sediments should be evaluated as potential alternative disposal media; and (iii) technical conservatism should be used in selecting and designing repositories. [Department of Energy, *Management of Commercially Generated Radioactive Waste* (DOE-EIS-0046-D, April 1979), vols. 1 and 2; *Proposed Rule Making on the Storage and Disposal of Nuclear Waste* (DOE/NE-0007, April 1980); *Report of Task Force for Review of Nuclear Waste Management* (DOE/ER-0004D, 1978); Interagency Review Group on Nuclear Waste Management, *Report to the President* (TID-29442, Washington, D.C., 1979); Office of the White House Press Secretary, *White House Message and Fact Sheet, the President's Program on Radioactive Waste Management* (Washington, D.C., 12 February 1980).]
3. High-level waste is defined as the liquid from the first extraction from the Purex process used for processing spent fuel. The liquid will be solidified into a leach-resistant form such as borosilicate glass.
4. W. P. Bishop and C. D. Hollister, *Nucl. Technol.* **24**, 425 (December 1974); D. R. Anderson *et al.*, *Impacts of Nuclear Releases into the Aquatic Environment* (International Atomic Energy Agency, Vienna, 1975), pp. 483–504.
5. High-level waste can be subdivided into fission fragments and transuranics, which have very different rates of radioactive decay. For fission fragments, times to decay to innocuous levels are typically less than 1000 years; for transuranics, they are up to 500,000 years. By the end of these periods, toxicity levels have fallen below those of naturally occurring radioactive sources. Most of the heat, which is generated by decay of the short-lived fission fragments, will be gone in 200 to 500 years. Therefore, the two periods of interest are (i) emplacement to approximately 200 to 500 years, during which large quantities of heat, with attendant thermal stress, will be released to the geologic formation and (ii) 500 to 100,000 or more years, during which thermal gradients are small but chemical and radiological gradients remain high.
6. A barrier is a mechanism or medium by which the movement of emplaced radioactive material is stopped or retarded significantly, or access to the material is restricted or prevented [A. Bauer, N. Dayem, R. Hall, *Off. Nucl. Waste Isolation (ONWI) Doc. 33(1) Draft* (October 1979); ONWI Staff, *ONWI Doc. 33(2) Draft* (November 1979)].
7. W. Bryan, G. Thompson, F. Frey, *Am. Geophys. Union Maurice Ewing Ser.* **2**, 273 (1979).
8. R. N. Anderson and M. D. Zoback, *Eos* **60**, 943 (1979); M. H. Salisbury, R. Stephen, N. I. Christensen, J. Francheteau, Y. Hamano, M. Hobart, D. Johnson, *Am. Geophys. Union Maurice Ewing Ser.* **2**, 113 (1979).
9. E. P. Laine, D. R. Anderson, C. D. Hollister, in *Wastes in the Ocean*, vol. 3, *Radioactive Wastes and the Ocean*, K. Park *et al.*, Eds. (Wiley, New York, in press).
10. J. Ryther, *Science* **166**, 72 (1969).
11. Large water masses (gyres) flow clockwise around the ocean basin in the Northern Hemisphere and counterclockwise in the Southern Hemisphere. The midgyre ocean basin areas are the most environmentally stable regions on the earth. A. McIntrye *et al.*, *Science* **191**, 1131 (1976).
12. An area of 10^4 km^2 will accommodate all the U.S. high-level waste through 2050 if the canisters are emplaced on 300-m centers.
13. T. H. van Andel, G. R. Heath, T. C. Moore, Jr., *Geol. Soc. Am. Mem. 143* (1975); T. C. Moore, Jr., T. H. van Andel, C. Sancetta, N. P. Sancetta, *Micropaleontology* **24** (No. 2), 113 (1978); T. A. Davies, O. E. Weser, B. P. Luyendyk, R. B. Kidd, *Nature (London)* **253**, 15 (1975).
14. Nodules with economically important quantites of copper and nickel are found chiefly below the fringes of the equatorial Pacific area of high biological productivity, many hundreds of thousands of kilometers from likely disposal areas. G. R. Heath, *Econ. Geol.*, in press; N. S. Skornyakova, *Deep-Sea Res.* **11**, 93 (1964).
15. North Pacific deep-sea red clay samples were taken from a 25-m core, LL44-GPC3 (30°19.9'N, 157°49.4'W). After original permeabilities were measured, two of the samples were remolded at the same water contents and permeabilities were again measured. Finally, the permeability of flow in (sediment drawn into the bottom of the core that was remolded in situ) was measured. Samples have permeabilities between 1.2×10^{-7} and 6.0×10^{-7} cm/sec.
16. D. F. McVey, K. L. Erickson, W. E. Seyfried, in *Wastes in the Ocean*, vol. 3, *Radioactive Wastes and the Ocean*, K. Park, D. Kester, I. Duedall, B. H. Ketchum, Eds. (Wiley, New York, in press).
17. S. Sourimjan and G. C. Kennedy, *Am. J. Sci.* **260**, 115 (1962).
18. R. W. Potter and D. L. Brown, *U.S. Geol. Surv. Open-File Rep. 75-636* (1973).
19. J. L. Krumhansl and G. R. Hadley, in *Workshop on the Use of Argillaceous Materials for the Isolation of Radioactive Waste* (Organization for Economic Cooperation and Development, Paris, 1979), pp. 221–231.
20. J. W. Braithwaite, in *Subseabed Disposal Program Annual Report*, D. M. Talbert, Ed. (SAND79-1618, Sandia Laboratories, Albuquerque, N.M., 1978), vol. 2, pp. 573–592; _____ and M. A. Molecke, *Nucl. Chem. Waste*, in press. Candidate alloys in oxygenated seawater (250°C; pressure, 7 megapascals; oxygen concentration, 1750 parts per million) have the following corrosion rates (millimeters per year): 1018 mild steel, 11.0; copper, 5.0; lead, 1.0; 90-10 cupronickel, 0.7; Inconel 600, 0.1; Hastelloy C-276, 0.2; and Ticode 12, 0.006.
21. The geothermal flux is generally on the order of 10^{-6} calories per square centimeter per second in the deep oceans (10^7 year old crust). However, some nonlinear gradients have been measured, and it has been suggested that these anomalies could be caused by large (kilometer-size) convection cells in the sediments or crustal rocks or both [R. N. Anderson, M. G. Langseth, J. G. Sclater, *J. Geophys. Res.* **82**, 3391 (1977); R. N. Anderson, M. A. Hobart, M. G. Langseth, *Science* **204**, 828 (1979)]. In one case, chemical gradients suggest much lower pore fluid velocities than do temperature profiles [J. Crowe and R. E. McDuff, *Eos* **60**, 863 (1979)]. Research to resolve this discrepancy should be encouraged. Nonlinear gradients have not been recorded in the most attractive areas for subseabed disposal in the western North Pacific, where tens of hundreds of meters of red clay blanket old crustal rock.
22. K. O. Emery, *The Sea off Southern California*,

a Modern Habitat of Petroleum (Wiley, New York, 1960), pp. 261–264.
23. A. Lerman, *Geochemical Processes, Water and Sediment Environments* (Wiley, New York, 1979), pp. 342–343.
24. K. L. Erickson, *Am. Chem. Soc. Symp. Ser.* **100**, 267 (1979).
25. D. Rancon and L. Brush, personal communication.
26. MODE Group, *Deep-Sea Res.* **25**, 859 (1978).
27. The key to retrievability of a waste canister is precise knowledge of its location. If it can be located—an achievement that requires only a small extension of current bottom-navigation techniques—we believe it can be recovered by technology comparable to that exemplified by the *Glomar Explorer*.
28. W. A. Nierenberg, *Am. Sci.* **66**, 20 (1978); M. N. A. Peterson, *Ocean Industry* (May 1969), p. 62.
29. Fine-grained abyssal clay formations have the plastic characteristics that they do not fracture if disturbed and they tend to seal-heal if disrupted [P. R. Dawson *et al.*, in *Waste in the Ocean*, vol. 3, *Radioactive Wastes and the Ocean*, K. Park, D. Kester, B. H. Ketchum, Eds. (Wiley, New York, in press)]. Since the sediments are soft, with an effective viscosity at the sediment-water interface near that of the overlying water, the system should respond in a hydrodynamic manner. If this is so, then when the pressure drop down the hole exceeds the small additional strength of the sediments, they will move in and close the hole. Preliminary results suggest that this will occur with red clay sediments when the penetrator has moved about 2 m into the sediments.
30. Department of Energy, *Environmental Impact Statement: Management of Commercially Generated Radioactive Waste* (DOE-1559, Washington, D.C., 1979), appendix N.
31. F. N. Spiess and J. D. Mudie, in *The Sea*, A. E. Maxwell, Ed. (Wiley, New York, 1970), pp. 205–250; F. N. Spiess and R. C. Tyce, *Scripps Inst. Oceanogr. Ref. 73-4* (1973).
32. International Atomic Energy Agency, *IAEA Inf. Circ. 205/Add.1/Rev. 1* (August 1978); 1972 Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, 26 U.S.T. 2403, TIAS No. 8165, entered into force 1975, reprinted in *11 Int. Leg. Mat.*, 1292 (1972); D. A. Deese, *Nuclear Power and Radioactive Waste* (Heath, Lexington, Mass., 1978), pp. 65–67.
33. D. R. Anderson, Proceedings of the Sixth Annual NEA-Seabed Working Group Meeting (SAND81-0427, Sandia Laboratories, Albuquerque, N.M., 1981). The countries are Japan, the United Kingdom, the United States, Canada, Netherlands, Germany, France, Commission of European Communities.
34. J. D. Isaacs and W. R. Schmitt, *Science* **207**, 265 (1980).
35. A. J. Russo, *Prediction of the Migration of Several Radionuclides in Ocean Sediment with the Computer Code IONMIG: A Preliminary Report* (SAND79-1666, Sandia Laboratories, Albuquerque, N.M., 1980), p. 17.
36. Supported by the DOE's National Waste Terminal Storage Program through a contract to Sandia Laboratories. Special thanks for stimulating discussions are due to R. Anderson, W. Bishop, V. Bowen, D. Deese, P. Dawson, G. Epstein, T. Ewart, L. Gomez, M. Harthill, R. Hessler, C. Hickox, E. Laine, M. Leinen, J. Lipkin, D. McVey, and P. M. Smith; for editing the many drafts of this article to C. C. Brown and R. Chandler; and for critically reviewing the manuscript and providing many important suggestions to G. Boyer, J. Crowe, J. Kelly, R. Klett, R. Lincoln, R. Lynch, R. McDuff, M. Percival, and J. Sclater.

Pheromones: Background and Potential for Use in Insect Pest Control

Robert M. Silverstein

Summary. Pesticides have not been a satisfactory solution to the control of insect pests. Pheromones show promise as a component of integrated pest management.

The biosphere has been drenched with insecticides, but effective, environmentally acceptable control of insect pests has not been achieved.

Because of its extraordinary toxicity in insects and relative safety in mammals, DDT was formerly hailed as the agricultural analog of penicillin, the modern miracle of medicine—and justly so. DDT killed insects that destroyed crops and were vectors of disease; crops flourished and millions of human lives were saved in the era including and following World War II. But in response to continual, excessive applications of the insecticide, the major insect pests developed resistance. Furthermore, populations of the natural enemies of major and minor pests were often reduced to ineffective levels. Thus the major pest population rebounded, and minor pests became major pests. The inevitable response of the farmer, under the urging of the insecticide salesman, was to further increase the dosage (*1*). Finally, the problems of environmental contamination by nonbiodegradable insecticides were brought home to the public by the appearance in 1962 of *Silent Spring* (*2*). Because of resistance and environmental problems, industry produced new insecticides, many of which were biodegradable but much more toxic to nontarget organisms. The honey bee and other beneficial insects, birds and other wildlife, and humans continue to be at risk, and the ratchet effect of increased resistance leading to increased dosage goes on.

This is by no means a plea for a total ban on insecticides. It would be as foolish to discard DDT and its analogs as to discard penicillin and its analogs simply because of the abuses committed in agriculture and in medicine. Retrospectively, the abuses are understandable. Both materials are extraordinarily effective and easy to apply, are manufactured cheaply in large quantities, and are made available in convenient form through defined channels: through insecticide salesmen directly to farmers; through pharmaceutical salesmen and practicing physicians to patients. Ideally, physicians prescribe the appropriate drug, but since they may lack time for continued training in pharmacology, they often find it convenient to accept the advertising literature and the urgings of the salesmen. Physicians may also accede to the demands of patients who have been conditioned to expect instant cures with miracle drugs. Farmers frequently have no buffer between themselves and the salesmen, and larger dosages mean larger returns to the salesmen and the manufacturers. In both cases, a sound concept is perverted to dubious use; the scientist proposes and the salesman disposes. In some instances, however, the farmer is well served by the local distributor whose interests are tied to those of the community. For example, Wilbur-Ellis Co. has effectively promoted integrated pest management programs and, in fact, helped carry out some of the programs that resulted in decreased insecticide use. The merits and limitations of conventional insecticides have been summarized and recommendations made for their use in systems of integrated pest management [see (*3*)].

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